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THESIS

AN INTELLIGENT AGENT SIMULATION OF SHIPBOARD DAMAGE CONTROL

by

Sylvio F. Andrade

June 2000

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AN INTELLIGENT AGENT SIMULATION OF SHIPBOARD DAMAGE CONTROL

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ABSTRACT

A fire on board a ship presents special challenges. It requires not only special anti-fire devices but well-trained teams of firefighters. Since crews rotate periodically, there is a need for ongoing personnel training and not all crew members have the same amount of training. A significant problem is how to assess the effectiveness of a team of firefighters with different skills in a real situation. A team should work together efficiently and follow standard procedures correctly if it is to successfully extinguish the fire within a reasonable period of time and with minimum damage. The question is: What skills are of most importance to a successful team of firefighters? It is difficult to carry out physical experiments without risking human lives and material losses. This thesis uses a reactive agent-based simulation to study the possible importance of different firefighting skills and anti-fire devices to the prosecution of fire on board a ship.

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EXECUTIVE SUMMARY

Personnel readiness for damage control is of great interest to navies. A fire on board a ship requires well-trained teams of firefighters. A significant problem is how to assess the effectiveness of a team of firefighters with different skills in a real situation. A team should work together and follow standard procedures to successfully extinguish the fire within a reasonable period of time and with minimum damage. As it is difficult to carry out physical experiments without risking human lives and material losses, simulation is a valuable alternative.

This thesis develops a reactive agent-based simulation to simulate a real fire environment and the interactions between the team of firefighters. It uses artificial intelligence techniques such as means-ends analysis and gathers information about the performance of the firefighting teams. A tentative illustrative stochastic model for fire spread is used to simulate the behavior of fire. The behavior depends on deterministic factors, such as the kind of material inside the compartment and its ignition and burn-out rates, and random factors, affecting fire growth, burn-out, and flashover. Note that the current model has not been calibrated using data or physical theory, but is useful as an illustrative tool. Each team member must accomplish a sequence of actions before and after extinguishing the fire. The duration of an action depends on the skill level of the team member in charge of the action.

Teams of firefighters with different skills should behave differently. To assess the readiness of different teams, we use the end time by which all actions have been accomplished in the simulation; to assess the damage caused by the fire, we use the final

amount of unburned material. Skill levels investigated were: 0.9 for a highly-skilled person, 0.5 for an average-skilled person, and 0.1 for a poorly-skilled person. Six different skill-level combinations were tested for firefighting teams composed of: a scene leader, an electrician, nozzlemen and hosemen. Three teams had members with the same skill levels (homogeneous teams), and three other teams had the same average skill level (non-homogeneous teams). One experiment used ignition rate 0.5, burn-out rate 0.25, and did one hundred runs for each of six combinations. A second experiment used ignition rate 1, burn-out rate 0.5, and did one hundred runs for each of six combinations. Other deterministic runs for homogeneous teams were made to check the behavior without randomness and flashovers.

One hypothesis is that the skill of the scene leader is the determining factor for the performance of a firefighting team. When time of completion is used to measure effectiveness, a good scene leader is not enough to assure a good performance, when unskilled nozzlemen and hosemen are part of the team. When the final amount of unburned material is used to measure effectiveness, there is not much difference among non-homogeneous teams of firefighters when both ignition and burn-out rates are high because the fire spreads faster and more material is burned out in less time. When both ignition and burn-out rates are reduced, the fire seems to be more difficult to extinguish, and we can get different results for teams with different skill levels.

The simulation suggests interesting results that might be used in practice. For instance, a team with an unskilled scene leader must have good hosemen and nozzlemen to maintain the same performance as one with a skilled scene leader. If good nozzlemen and hosemen are not available for all sections of a ship, a wise choice is to assign them to a section with low ignition and burn-out rate compartments where there is a greater chance of avoiding damage losses than in compartments with high ignition and burn-out rates.

This thesis suggests the need, and can provide the basis for more detailed models. Team members can be added with new actions to carry out; the parameters for ignition rate, burn-out rate and type of fire can be changed; models for the spread of smoke can be used; and different mathematical models for the spread of fire can be used to simulate the behavior of fire, including the spread of fire to other compartments and the dynamic allocation of firefighters.

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I. INTRODUCTION

A. AREA OF RESEARCH

The purpose of this thesis is to use an agent-based simulation to make a quantitative assessment of the effectiveness of a team of firefighters when responding to a fire-on-board situation. The agent-based part of the simulation utilizes the METutor package. A stochastic model simulates the fire spread; it simulates the effects of fire in different compartments with different inflammable contents and anti-fire features when a team of firefighters attacks it. The simulation enables performance comparison of teams of firefighters with different skill levels.

B. OBJECTIVES AND RESEARCH QUESTIONS

An important issue in a damage-control situation involving fire is how fast that fire may spread inside a compartment with or without anti-fire devices, based on the time and skill of reaction of a team. Part of that skill is situational awareness. How quickly might a team with different skill levels put out or control a fire in a compartment? What measures of performance and effectiveness best summarize their performance (for example, the expected or median time until a fire is out, expected or median damage to compartment contents, risk/probability of total inflammation/burn up, and probability of injury or death of a team member)?

All these measures depend on factors such as time and correctness of response. What should be the composition of a team to accomplish all the tasks needed to put out a fire? How effective is a sequence of actions that comprise a standard procedure like setting boundaries for possible fire spread, use of anti-fire devices such as hose, foam, halon, and CO_2, verification that a fire is out, testing of O_2 level, removal of smoke from the area, removal of water from the area? What happens if incorrect or improper orders are given by unskilled team members, or orders are not followed correctly, or are late? How do combinations of such mistakes affect the extinguishing of the fire?

C. SCOPE OF THESIS AND METHODOLOGY

The scope and purpose of the thesis is to develop and test a multi-agent simulation program module of a firefighting team which integrates unique real-world elements and subjective characteristics of human beings such as knowledge, experience, communication and coordination.

Since a physical experiment is very difficult to reproduce and test without any risk to human lives and expensive resources, an agent-based simulation is used to study the effectiveness of a firefighting team. The simulation models the fire and the effects of sequences of actions required to put out a fire. These actions vary with the size of compartment, how the fire spreads, the type of the fire, communications between the team members, and the skill levels of the team members.

The agents in this multi-agent simulation are models of members of the team, the command center, and the fire itself. Agents are defined as software modules with more autonomous capabilities than most software components, typically including reasoning, communication and decision-making. In this simulation, agents react to external events produced by other agents including the fire, but, unlike adaptive agents, do not change their rules in response to new environments.

Actions (such as approaching the fire, extinguishing the fire, testing the gases, and removing the smoke) require specific preconditions be achieved so that they can be carried out. The skills of the executor influence the duration of each action and the overall time to complete the mission. Agents use orders and reports to communicate and coordinate actions.

The Prolog programming language and METutor package are used to provide computerized artificial intelligence input to the model of the situation. The artificial-intelligence means-ends algorithm is used to build action sequences from a given start state to a goal condition by a sequence of state transitions. The algorithm permits the modeler to specify the possibility of random events such as casualties, availability of a doctor, faulty (possibly broken) lines of communication, and equipment malfunctions that can influence the outcome of the simulation.

Analysis of firefighting approaches requires assessment of teams with members of different skill levels and different numbers of members who must interact and follow specified policies. Simulation output analysis leads to conclusions about the successful composition and basic tactics of a team. Measures of effectiveness for firefighting include the mean and median fire duration as a function of firefighter skill level, and the mean and median material burned as a function of firefighter skill level (the median is less susceptible than the mean to long durations and extensive destruction). Histograms, as in Figures 4-1 to 4-6, indicate that fire durations can have exceedingly variable, and occasional long, durations. The median does not reflect these.

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II. BACKGROUND

The subject of this thesis is a simulation model of a shipboard emergency response team fighting a fire. In this chapter we describe the initiation and progression of a fire, the methods used to fight a fire, and the organization of a team responding to a fire. The first section of this chapter summarizes how a fire spreads, how it is classified, and what kind of devices and personnel are necessary in different situations. The second section describes the basic composition and organization of a team of firefighters, as well as a sequence of firefighting actions and the personnel needed to carry them out. The third section describes the importance of a well-skilled team, and how this can be achieved. The fourth section describes artificial-intelligence methods that can be used to make a simulation mimic human behavior. The fifth section describes the agent-based approach that we use for simulation.

A. FIRE FACTS

Once started the fire may go out if its combustibles are isolated [Ref. 1:pp.1-9]. But usually the fire spreads to other material, depending on their mutual configuration. Ignition rates (rates with which combustibles catch fire) differ for solid fuels and, for example, are greater for dust or shavings than for bulky materials (so small wood chips will burn faster than a solid wood beam because more vapors are available for ignition). "Ignition rates are measured in kilowatts (kW); one kW is approximately 0.95 BTU/min". While the fire is burning, the material that has been on fire gradually becomes no longer inflammable; the rate of this is called the burn-out rate (a function of the fire size and the kind of inflammable material). An anti-fire action can affect both the ignition rate and the burnout rate. As a fire is extinguished, the temperature and the ignition rate decrease. During extinguishment, the burn-out rate usually increases due to materials that become unable to burn.

"There are four classifications of fires: class A, class B, class C and class D. Class A fires involve wood and wood products, cloth, textiles and fibrous materials, and paper. Class A fires should be extinguished with water in a straight (stream) or fog pattern (spray). If the fire is deep-seated, aqueous film foam (AFFF) is more effective than seawater and can be used as a wetting agent to rapidly penetrate and extinguish the fire. Class B fires involve flammable liquids such as gasoline, diesel fuels, jet fuels, hydraulic fluid, and lubricating oil. These fires are normally extinguished with AFFF, Halon 1211, Halon 1301, or potassium bicarbonate (PKP). Class C fires are energized electrical fires that are attacked at prescribed distances using nonconductive agents such as CO_2 , Halon 1211, or water spray. The most effective tactic for a class C fire is to deenergize the compartment and handle the fire as a class A fire. Class D fires involve inflammable metals such as magnesium and titanium. Application of water in quantity, using fog patterns, is the recommended tactic. When water is applied to burning class D materials, there may be small explosions; the firefighter should apply water from a safe distance, or from behind, shelter. Metal fires on board ship are commonly associated with aircraft wheel structures" [Ref. 1:pp.1-13].

"There are many materials that may be used as firefighting agents. Examples are water, aqueous film-forming foam (AFFF), carbon dioxide (CO_2), and halon. Water is a cooling agent and, on board a ship, the sea provides an inexhaustible supply. If the surface temperature of a fire can be lowered below the fuel's ignition temperature, the fire will be extinguished. Water is most efficient when it absorbs enough heat to change to steam; the steam carries away the heat, which lowers the surface temperature. Water in the form of a straight stream is used to reach into smoke-filled spaces or areas at a distance from the firefighter. It should be directed into the seat of fire, and for maximum cooling the water must come in direct contact with the burning material. Water fog or spray is very effective for firefighting. However, it must be applied directly to fire if its benefits are to be realized. Additionally, a team that uses a hose with a fog nozzle can protect firefighters from both convective and radiant heat during the extinguishing action.

AFFF is composed of synthetically produced materials similar to liquid detergents. These film-forming agents form water-solution films on the surface of flammable liquids. AFFF diluted with water provides three fire extinguishing advantages. First, an aqueous film is formed on the surface of the fuel, which prevents the escape of the fuel vapors. Second, the layer of foam effectively excludes oxygen from the fuel surface. Third, the water content of foam provides a cooling effect.

Extinguishing fires by smothering is possible with the inert gas CO_2. It is 1.5 times heavier than air, so it tends to settle and blanket the fire. It is a dry, non-corrosive gas which is inert when in contact with most substances, and it will not leave a residue and damage machinery or electrical equipment. In both the gaseous state and the finely divided solid (snow) state, it is a nonconductor of electricity regardless of voltage, and can be safely used in fighting fires that would present the hazard of electric shock.

Halon is a halogenated hydrocarbon with nonflammability and flame-extinguishing properties. Both Halon 1211 and 1301 chemically inhibit the flame front. Halon 1301 is used in fixed flooding systems for extinguishing flammable liquid fires.

The short discharge time of Halon 1301 (10 seconds maximum) helps keep the thermal decomposition products well below lethal concentrations. Personnel should not remain in a space where Halon 1301 has been released to extinguish a fire without a breathing apparatus. When released in engine enclosures, approximately 15 minutes is required before reentry [Ref. 1:pp. 1-22, 23, 24].

Most ship compartments do not have installed automatic fire-extinguishing systems such as active sprinklers or CO_2 flooding. When such compartments are on fire, mobile anti-fire apparatus operated by a team of firefighters is needed. However, special rooms such as an ammunition magazine must have active sprinklers to prevent chain reactions, while others such as the Main Machinery Room and the Pump Room must have halon, CO_2, and AFFF installed inside or nearby".

B. FIREFIGHTING ORGANIZATION AND PROCEDURES

The most common shipboard emergency is fire. US Navy Ships organize their primary emergency-response team as a fire party made up of people with the different skills needed to combat emergencies. A ship must determine the availability of personnel and materials and design an organization for the employment of personnel and equipment to combat fires and respond to other emergencies. Specific responsibilities, duties, and employment of equipment must be assigned to individuals, divisions, or departments. This information is put into a comprehensive form called a *Fire Bill* and is made available to all personnel addressed in the document. The purpose of the Fire Bill is to establish a firefighting organization and specify responsibilities for individuals and departments to ensure that fires and other related emergencies are effectively and quickly handled.

Fires or emergencies that occur during combat or while the ship is at *General Quarters* should be handled as battle casualties by the Repair Party organization in that section of the ship which reports to their General Quarters stations on Fire Call. While the ship is in port, the ship's Fire Bill may designate the In-port Fire Team as the primary firefighting team. The In-port Fire Team is composed primarily of personnel in the regular damage control repair parties, so each duty section must have an effective firefighting force. The number of people in the fire party assigned to a fire will vary depending on the nature of fire and the number of people available. There can be a large turnover of personnel assigned to repair parties, so repair party personnel may not be familiar with the location of damage-control equipment.

The member of a team in charge of firefighting at the scene of a fire is the *scene leader*. He directs the attack against the fire and communicates with the repair party leader via messenger. He must be capable of making correct decisions during a changing situation based on his assessment of the current state. The scene leader is located a short distance from the fire, and his assessment must be derived from the reports he receives. Scene reports can contradict previous reports due to unexpected events such as human errors, personnel casualties, fires reflashing after being previously extinguished, and equipment malfunction. Nevertheless, a scene leader must continually reassess the needed response as a result of the reports. He must always investigate unsatisfactory or incomplete reports from the scene; for instance, if an unskilled member fails to report the end of a task or does not know what to do, the scene leader may order that action again to ensure its satisfactory completion. The scene leader relays information to the damage control assistant (at a place that we refer as the *Command Center* in our simulation) to keep it updated and to receive further instructions.

The fire attack team consists of an optional attack scene leader, and one or two hoses manned by *nozzlemen* and *hosemen*. The attack scene leader directs the nozzleman in employment of the hose, directs the hosemen, directs that the hose be charged or secured, selects the water pattern to be used, and directs the rotation of attack team personnel. Generally, the nozzleman works the hardest and will need to be relieved first; rotating the nozzlemen and the hosemen can extend the endurance of the attack team. The attack team can be supported by other emergency response team members such as an electrician (responsible for deenergizing, reenergizing, and desmoking the area), investigators (responsible for testing for gases and oxygen after fire is out and for monitoring the oxygen-mask control time of nozzlemen and hosemen for rotation purposes), hospital corpman, and dewatering and desmoking teams when personnel are available. Communications are often disrupted, so voice amplifiers should be provided to the members of a fire party.

There is a preferred sequence to completing major actions while combating a fire. For example, if only 90% of a fire is extinguished and an order to desmoke is given, the high rate of airflow from the desmoking fans will cause the fire to increase in intensity. Fire team members must understand the general order of actions or strategy of combating a fire and how to effectively concentrate available resources to carry out these actions. In addition to strategic knowledge, the scene leader must understand the details of every other member's job and equipment to differentiate between satisfactory and unsatisfactory reports. For example, he must know that 16% oxygen is inadequate to sustain human breathing, whereas 21% is satisfactory indefinitely. The factual knowledge of a scene leader must cover a wide range of functions and equipment.

A sequence of actions and reports takes place during firefighting. Reports announce the class of the fire, actions taken to isolate and combat the fire, that the fire is contained, that the fire is out, that the reflash watch is set, that the compartment is ventilated, and that the compartment is tested for oxygen, flammable gases, or toxic gases. Some actions must be coordinated with reports from the fire scene. Generally, the first step is to go to the repair locker and assemble equipment. Once at the scene of the fire, the leader appraises the state of fire and determines its precise location using men with breathing apparatus and thermal imagers for large fires involving much smoke. The leader must select the appropriate tactics to attack the fire and choose appropriate tools. Fire boundaries must be established, and the area must be deenergized to avoid potential injuries. Now team members with firefighting equipment can approach the fire. If during extinguishment the team leader perceives that the fire is not decreasing, he may order a change of tools. If the fire situation becomes worse and the fire becomes uncontrollable he may decide to isolate the compartment. However, if the fire decreases and eventually goes out, desmoking and dewatering takes place, and the area is reenergized and ventilated. Then the leader orders a watch for a reflash (means fire can start again); if nothing else happens, the team can return to the repair locker, store the equipment, and receive a debrief of the action.

C. FIREFIGHTING TRAINING AND SKILLS

The best organization and equipment are useless without trained personnel. Properly drilled crewmen will minimize confusion during fires, increase the probability that proper actions are taken, and enhance the predictability of responses and tactics. People assigned to a firefighting party should retain that position even if other shipboard duties change. In the U.S. Navy, they are required to meet the damage control training requirements specified in the General Damage Control Qualification Standard within 6 months of reporting aboard. The time to train an individual for both General Damage Control and for a specific job on a fire team can take up to 8 months depending on the individual's motivation and learning ability. In a shipboard environment, duty assignments rotate frequently and maintaining a large group trained and fully qualified is a problem. So, all members of a fire party should be cross-trained for at least one other position in the fire party to compensate for frequent rotation [Ref. 2:p.15], and everyone on the ship, particularly on small ships, should be trained to serve on a fire party [Ref. 1:pp.9-1].

U.S. Navy Ships today typically conduct a daily drill or formal instruction for inport fire teams. Effective fire teams gain experience through numerous hours of realistic drill supplied by a knowledgeable drill team. The drill team can supply realistic details (e.g. smoke, flames, personnel injuries), challenge fire-team members with difficult jobs, provide a realistic shipwide casualty environment, and conduct an effective debriefing of each person's actions. However, a knowledgeable drill team to execute this kind of training aboard is not always available.

Intelligent Computer-Aided Instruction programs could be a cost-effective substitute for some firefighting instruction although missing the physical aspects of the task. "Procedural skills in events like firefighting require a sequence of actions to achieve some desired result, and "learning by doing" by using computer simulations is often a good way for students to learn and practice these skills. Technical organizations such as the US Navy, demand that students learn a wide range of reactive and technical procedures. Learning these skills becomes especially challenging when it is necessary to choose between actions with context-dependent effects [Ref. 3]".

Intelligent Computer-Aided Instruction programs like FIRE [Ref. 2], and authoring systems like MEBuilder and METutor [Ref. 3] are tools for constructing intelligent simulation-based tutors for procedural skills. The tools use planning methods, consistency enforcement, objects, and structured menus to make writing tutors easier than with conventional authoring software. An instructor can create lessons and simulations for hands-on training without many resources. Students can learn at their own pace, with minimal direct supervision from a teacher. Instructional computer programs can describe realistic problems; they can challenge knowledge of job responsibilities and equipment operation; they can describe a realistic shipboard environment; keep records of student performances; and tutor when an incorrect action is chosen. "Therefore, simulation-based tutors for procedural skills could improve the quality of training for damage control and emergency procedures, and could sharpen "almost-right" skills of people who need "refresher" or "checkup" validation periodically, a frequent circumstance in the military [Ref. 4]".

D. MEANS-ENDS ANALYSIS

In this section we describe the computer modeling of sequences of actions used in firefighting. Firefighting knowledge can be envisioned as a tree of tasks where nodes represent a sequence of linked actions and subactions which team members must execute to recover from a fire (see Appendix C). The tree results from a top-down stepwise refinement design. An expandable-action node corresponds to an action which can be broken down into subactions. There is a preferred order for most major firefighting actions if we are to model the way an expert scene leader would handle a fire episode. If a subaction is not completed, a negative report is received, and that subaction must be redone.

A data structure needs to represent possible states during a fire episode. Two states are special: a given start state (set of initial facts) including a fire, its size, type and location (although this is initially unknown to the fire team), and a given goal (state in which objectives have been achieved), such as "all fires are out and the ship is restored to normal operation". Searching through the possible states results in a path of states from start state to goal which can be followed by the simulation. The procedure used to find the path is *means-ends analysis* [Ref. 5:pp. 263-270], a search method using top-down recursive decomposition of a search problem into simpler subproblems. This structure uses a "difference table" showing the recommended major action for any search problem. It is specified by assertions of the form "recommended (<difference list>, <action>)" which gives conditions for recommending an action based on the facts different between the current state and the goal. The operator will not necessarily be able to apply the recommended action immediately, but the action should be the most important one necessary to solve its search problem at any moment.

Each action has preconditions (facts that must be present in a state before we can do the action); these are specified by facts of the form "precondition (<action>, <precondition-facts>)". Once an action is done, the state is changed: some facts become true and some facts become false. For those conditions that become true, an "addpostcondition (<action>, <added-facts>)" fact is used, and for the facts that become false, a "deletepostcondition (<action>, <deleted-facts>)" fact is used. Addpostcondition and deletepostcondition facts convey both intended and side effects of an action, such as "fire is out" and "area is watery" (addpostconditions) and "it is no longer true that boundaries are set" (deletepostconditions) for the "extinguish" action. They also convey state-dependent effects, such as "there is damage to the floor" when the user forgets to turn the power off before extinguishing the fire.

E. AGENT-BASED ENVIRONMENTS

Firefighting simulations fit well the paradigm of intelligent multi-agent simulations. An intelligent agent is software with *autonomy, adaptation and cooperation* [Ref. 6:pp. 1-5]. Multi-agent systems are computational systems in which several agents interact to achieve their goals. In the human world, complex jobs are usually performed by several individuals because individual capabilities are limited to some extent. Analogously, agents in the multi-agent system communicate, coordinate, and negotiate with one another to achieve goals. There are three aspects of agents:

- *reactivity*: to what degree agents have an internal representation of the world.
- *deliberation*: to what degree agents have a symbolic representation of the world using beliefs, goals, and intentions, and possess logical inference mechanisms to make decisions based on their representation.
- *sociability*: to what degree agents coordinate their activities with those of the other agents through communication.

Agents used in the firefighting simulation have these properties except the ability to adapt themselves through learning.

Agents' models for real applications often address complex, dynamic, and nondeterministic, uncertain, environments. Thus they need to represent worlds with exogenous events, other agents, uncertain effects, and social interactions. The interaction and synchronization between agents can be accomplished by protocols for communication. Protocols govern the sending of messages between social agents and monitoring of execution. An agent has knowledge of its internal control mechanisms, or in other words, it knows how to make behaviors, problem-solving methods, and strategies work together in order to achieve its goals. Means-ends analysis accomplishes this for the firefighting simulation. Agents can also have purely reactive behaviors, a necessary ingredient for the design of real-time multi-agent systems. A fire agent is an example of reactive agent since its behavior is based on a mathematical model: it responds to other agents' actions (such as extinguishing) or events (a possible *flashover).*

III. PROPOSED MODEL

A. PROPOSED SIMULATION

The firefighting models proposed here are agent-based with some random behavior. There are six agents in our simulation: *command center, team scene leader, nozzleman, hoseman, electrician* and *fire*. The agents nozzleman and hoseman could represent several people.

The fire agent received special attention in our simulation. The fire will only be noticed if it grows above a certain limit inside a compartment. The kind of inflammable will determine the type of fire and thus the necessary tools and tactics. Then the fire will spread inside the compartment until the team of firefighters starts to extinguish it. We used a simple stochastic epidemic-like model for the fire agent [Ref. 7.] The model assumes that the growth of a fire is a function of the amount of unburned inflammables and the rate with which inflammables catch fire (the ignition rate). The model includes the feature that items on fire can burn out (the combustibility of each elementary item), and once a unit is burned out, it cannot burn again. Both ignition and burn-out rates have random fluctuations during a fire and from fire to fire. The number of unburned combustibles at any time is a function of the pattern of fire growth. When extinguishing is being carried out, the ignition rate generally decreases and the burn-out rate increases, and both depend on the skill of the team member in charge of extinguishing. If the extinguish action is successful, the fire will eventually go out (so fire size will equal 0).

The fire model allows partial flashovers (when a fire grows unexpectedly but ignites only part of the intact (unburned) inflammables), and total flashovers as well.

Both may happen with a certain probability. A total flashover ignites all intact combustibles, increasing the size of fire and making the number of unburned combustibles go to zero very quickly. The probability of occurrence of a flashover is a function of the size of fire, the temperature in the region, and the number of inflammables on fire. The model for firespread and flashover is speculative and illustrative, and currently not calibrated to actual fire data or to high-resolution models based on physical principles. It is planned to carry out such steps in future.

Each member of the firefighting team has a skill level. This parameter influences the duration of the actions "equip", "extinguish", "desmoke", "dewater" and "watch for reflashing", because these are the most important firefighting actions. Actions have durations which are assumed to be independent random variables whose mean and range are a function of the action, the agent, and the current state. The duration of the extinguishing action, however, depends on the behavior of the fire, as will be explained.

B. A MATHEMATICAL MODEL OF FIRE GROWTH

The stochastic model for fire spread is as follows. Suppose the shipboard compartment contains a quantity C of inflammable items (in the implementation C(0), the quantity at time 0, is 100). Let us assume that they are all equally inflammable for the present; also, let us ignore spatial considerations for the present. Let X(t) denote the number of inflammable units on fire at time *t;* this number is a continuous variable with $0 \leq X(t) \leq C(0)$. The fire starts with X(0)=X, and then spreads until items are on fire simultaneously. Items on fire eventually burn out (the combustibility of the item becomes exhausted).

The fire spreading described resembles a SIR (Susceptible, Infectious, and Removed) *epidemic* model used in epidemiology and public health; see e.g. Gani and Daley (1999). Such a model can be relatively easily studied deterministically using differential or difference equations, and also stochastically, possibly using Markov chains if the "population" size, C, is not too big. It is proposed here that fire progression be modeled in this way. Epidemic models for such processes do not normally consider a flashover phenomenon, so we will postpone its consideration.

Let X(t) be the number of inflammable/combustible elements on fire at *t,* and let C(t) be the number of inflammable/combustible units unburned at *t.* In epidemic theory X(t) represents *infectives* and C(t) represents *susceptibles.* An inflammable element burns for awhile and then becomes burned out, but while is burning it may ignite more inflammable elements. According to this model:

$$X(t+h) = X(t) + \underbrace{\lambda h X(t)C(t)/C(0)}_{\substack{\text{New ignitions in (t,t+h)} \\ \text{for ignition rate } \lambda}} - \underbrace{\mu h X(t)}_{\substack{\text{Burnout in (t,t+h)} \\ \text{for burn-out rate } \mu}} \tag{3.1}$$

Since C(t) inflammables are immediately reduced to C(t+h) with fire spread to X(t), we have

$$C(t+h) = C(t) - \lambda h X(t)C(t)/C(0) \tag{3.2}$$

In the limit for small h we obtain the differential equations:

$$\frac{dX(t)}{dt} = \lambda X(t)C(t)/C(0) - \mu X(t) \tag{3.3}$$

$$\frac{dC(t)}{dt} = -\lambda X(t)C(t)/C(0) \tag{3.4}$$

Note: $C(0) - C(t) - X(t)$ is the number of inflammable units burned out at *t,* where $C(0)$ is the initial number of inflammable units; this burn-out increases as the fire burns. If λ is small compared to μ, then fires can go out on their own accord.

C. STOCHASTIC FIRE SPREAD (GAUSSIAN APPROXIMATION)

Fire spread can be more realistically modeled as a random process. Suppose that the competition between fire growth and decay can be represented as a deterministic term ("drift") plus Gaussian /normal increments. Then:

$$\mathbf{X}(t+h) = \mathbf{X}(t) + \boldsymbol{\lambda}\mathbf{h}\mathbf{X}(t)(C(t)/C(0)) - \mu h\mathbf{X}(t)$$

$$+ \boldsymbol{\sigma}_\lambda [(\mathbf{X}(t), \mathbf{C}(t)] \mathbf{Z}_\lambda(t) - \boldsymbol{\sigma}_\mu [(\mathbf{X}(t),\mathbf{C}(t)] \mathbf{Z}_\mu(t) \tag{3.5}$$

where here:

$\lambda h\mathbf{X}(t)\mathbf{C}(t)/C(0)$ represents the mean incremental fire growth (3.6)

$\mu h\mathbf{X}(t)$ represents the mean incremental burn-out growth (3.7)

$\boldsymbol{\sigma}_\lambda [\mathbf{X}(t),\mathbf{C}(t)] \equiv \sqrt{\lambda h\mathbf{X}(t)\mathbf{C}(t)/C(0)}$ represents the standard deviation of the incremental random fire growth (3.8)

$\boldsymbol{\sigma}_\mu [\mathbf{X}(t),\mathbf{C}(t)] \equiv \sqrt{\mu h\mathbf{X}(t)}$ represents the standard deviation of the incremental random burn-out (3.9)

and $\mathbf{Z}_\lambda(t)$ and $\mathbf{Z}_\mu(t)$ are normally distributed with mean 0 and variance 1, and $\{\mathbf{Z}_\lambda(t)\}$ and $\{\mathbf{Z}_\mu(t)\}$ are mutually independent sequences of independent and identically distributed Gaussian random variables.

The decline of the intact unenflamed items can be similarly modified to:

$$\mathbf{C}(t+h) = \mathbf{C}(t) - \lambda h\mathbf{X}(t)\mathbf{C}(t)/C(0) - \boldsymbol{\sigma}_\lambda[\mathbf{X}(t),\mathbf{C}(t)]\mathbf{Z}_\lambda(t) \tag{3.10}$$

Note if a random fluctuation in $\mathbf{X}(t)$ is positive, represented by a positive value of $\mathbf{Z}_\lambda(t)$, this must mean a negative fluctuation in the unburned material, $\mathbf{C}(t)$. Note that the last term has a negative sign although $\mathbf{Z}(t)$ can be of either sign.

It is necessary to make sure that boundary overshoots do not occur when using the difference equations; if overshoot occurs, we replace $\mathbf{X}(t)$ or $\mathbf{C}(t)$ by the boundary value 0 or C.

D. GAUSSIAN FIRE SPREAD WITH TOTAL FLASHOVER POSSIBLE

Equations 3.5 and 3.10 can be modified to allow for total flashover. We use Equation 3.5 and Equation 3.10 with probability $1 - \varphi\ [(\mathbf{X}(t),\mathbf{C}(t)]$, when there is no flashover, and $\mathbf{X}(t+h)=\mathbf{X}(t)+\mathbf{C}(t)$ and $\mathbf{C}(t+h) = 0$ with probability $\varphi\ [\mathbf{X}(t),\mathbf{C}(t)]$, when there is a total flashover . The function φ increases monotonically with X so that there is an increasing probability of flashover. An example of φ is:

$$\varphi(t) = [1 - \exp(-\gamma h(\mathbf{X}(t)(C-\mathbf{C}(t))/C))] \tag{3.11}$$

where the flashover constant parameter γ is 1. This is an illustrative function, not one that has been physically validated.

E. FIRE MODEL WHEN FIRE IS BEING EXTINGUISHED

The fire model when undergoing extinguishing is similar to the normal spread model except for the values of ignition rate and the burn-out rate. The new ignition rate is a function of the old ignition rate and the skills S of the team member in charge of extinguishing such that the greater the skills, the lower the ignition rate. We use (for illustration):

$$\lambda_{New} = (\lambda_{Old}) \exp(-10S) \tag{3.12}$$

The new burn-out rate is similarly affected by the skill level (again illustrative):

$$\mu_{New} = (\mu_{Old}) \exp(S) \tag{3.13}$$

F. MODELING OF FIREFIGHTING PROCESSES

To model the human behavior in firefighting we use planning methods from artificial intelligence to determine the sequence of actions performed. A list of facts describes each planning state. The initial conditions for our model comprise the locations where fire may start (such as the engine room or ammunition magazine), the ignition and burn-out rates for the material inside the compartment, the quantity of inflammables (which was 100 for our test runs), the type of fire (e.g. type a, b, c, or d), and the initial size of fire and smoke (e.g. one and zero). Fire will not be noticed until its size is big enough (more than 1.5 in our test runs) to activate an alarm inside the compartment.

Each animate agent (fire scene leader, nozzlemen, hosemen, electrician, or command center), has a specific goal to be achieved, so they have *goal-directed behavior.* These agents use means-ends analysis to figure what to do when they are unoccupied. Each agent then plans a way to achieve its goals, and chooses one action from the plan to execute first. An agent can be *active* (doing a task), *idle* (if its goals are achieved), or *waiting* (if its goals are not achieved but it has nothing it can do). At each step in the simulation, the active agent that has been least recently updated gets a chance to plan. When an agent is idle it can be awakened by specified triggers such as orders given it or reports received by it.

Each action has a specified set of possible agent "actors"; the agent waiting the longest is assigned the action if more than one agent is available. Some complicated actions also require the presence of assistants to the actor, such as the hoseman to hold the hose while the nozzleman is extinguishing the fire; such actions require that the assistant be waiting as well as the actor for the action to proceed.

There are two different ways to choose an action. With "first doable operator" the agent executes the first action in the plan (generated as explained below) that is possible, whereas with "random doable operator" the agent chooses a random possible action in the plan. A possible action must be permitted by preconditions, recommended at the given time, and must not be in progress already. The implementation uses the "random doable operator".

The simulation of actions also adjusts the states with results of terminating concurrent actions and ensures no two actions end at the same time to prevent confusion in state reasoning. The simulation permits actions to be aborted by other actions in high-priority circumstances. For instance, a fire may reignite at random when a crewman is ventilating a compartment; the crewman then ceases ventilation and initiates immediate fire extinguishment steps. Actions are also aborted when their preconditions become false during their execution.

Means-ends analysis (see chapter 2) is responsible for the planning for each animate agent. It decomposes a complicated task into simpler subtasks until all subtasks can be accomplished by single actions. Appendix C describes the tasks an agent must carry out, and Appendix D shows the sequence of tasks for an example simulation run.

A list of actions needed to achieve particular facts, not necessarily actions that can be performed immediately, is used as recommendation conditions. For example, the "ventilate" action is recommended whenever the gases or oxygen are to be made safe, and they are known to be unsafe. On the other hand, the preconditions of "ventilate" (facts that must be true beforehand) are that the fire team must be at the location of the fire, the team must be equipped, and the fire is out.

The state of the system will be affected by the "ventilate" action as some facts become false and will be deleted from the previous state ("deletepostconditions") and other facts will be true and will be added to the previous state ("addpostconditions"). The postconditions of "ventilate" are that gases and oxygen are safe, gases and oxygen are no longer tested, and smoke is removed. Random postconditions model uncertainties and accidents in the simulation. For instance, when an agent has to test gases, there is a probability (for example, of 0.3) that gases are unsafe. Random changes are applied to the state after regular postconditions are applied.

Each action has a duration which is a random variable whose mean and range can depend on other parameters, such as the skill of the assigned agent, the fire size, the kind of tool used, smoke intensity, and water magnitude. To each team member we assign a number between 0 and 1 that represents a subjective measure of their skill level, where the higher the number the better the skill. Uniform distributions are assumed for durations. For instance, order and report actions have a mean of 0.25 minutes and a range of 0.1(0.15,0.35), and the action of watching for a reflash has a mean of 15 minutes and range of 5 minutes (10,20). The time to "dewater" has a mean of the product of 0.15 and (WaterQuantity/Skill) and a range of the product of 0.12 and (WaterQuantity/Skill), and "desmoke" has a mean of the product of 0.8 and (Smoke/Skill) and a range of the product of 0.6 and (Smoke/Skill). Other actions have a mean of 1 minute and a range of 0.5. These are just rough estimates for illustrative purposes; determination of trustworthy submodels for the entire process remains a significant practical task.

The fire model discussed earlier is implemented with a fire agent. A one-minute time step is used by the fire agent to update size of fire and number of intact inflammables. The fire is monitored at time steps of 5 minutes. If fire does not seem to decrease during the extinguishment process, the team realizes this and changes anti-fire tools with a probability of tool failure (FSize/(FSize+(100*Skill))), where Fsize is the size of fire and Skill is the skill level of the team member in charge of the extinguishment. The model does not allow the number of inflammables to be more than the initial number of inflammables or less than 0.001.

This simulation has been implemented by a program written in Quintus Prolog, taking advantage of several Quintus Prolog library modules such as "math" and "random" libraries. The simulation is implemented as two files: a problem-dependent part ("fireagents") and problem-independent machinery for running multiple agents in means-ends simulations ("meagent"). The latter is complex and includes general control of the agents' actions with code from METUTOR system [Ref. 3] for procedural modeling of goal-directed behavior.

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IV. OUTPUT ANALYSIS

A. METHODOLOGY

Simulation trials were carried out to assess teams with different skill levels in firefighting. One hundred trials were done for each of several sets of parameters. Skill levels were illustratively chosen as follows: 0.9 for a high skill level, 0.5 for an average skill level and 0.1 for a poor skill level. There are 27 possible skill combinations for a team of four members if the nozzlemen and the hosemen have the same skill levels. Six cases of special interest were: an ideal team (all members with 0.9 for skill level); an average team (all members with 0.5 for skill level); a poorly-skilled team (all members with 0.1 for skill level); a team with highly-skilled scene leader, average-skilled hosemen and nozzlemen and poorly-skilled electrician; a team with average-skilled scene leader, poorly-skilled hosemen and nozzlemen, and highly-skilled electrician; and a team with poorly-skilled scene leader, highly-skilled hosemen and nozzlemen, and average-skilled electrician. The average skills in all of the above non-homogeneous teams are the same.

Two kinds of fire locations were used: a highly inflammable compartment with pre-extinguishing ignition and burn-out rates of 1 and 0.5 respectively; and a compartment with pre-extinguishing ignition and burn-out rates of 0.5 and 0.25 respectively (the rates are modified when the extinguishing action starts using equations 3.12 and 3.13); both locations had the same flashover probabilities (see equation 3.11). For each six combinations of skills, one hundred replicate runs were executed, and summary data were recorded.

We assume that the total time for firefighting is the time elapsed between the first appearance of the fire (time 0) and the reporting of the completion of both extinguishment and debriefing. Also, an upper limit on simulation duration of 400 minutes is enforced in cases when the fire burns out but recurs sporadically, never exceeding the alarm threshold. Otherwise, the mean time for the set of one hundred runs could be unfairly high, though the median is a useful alternative summary estimate.

B. ANALYSIS OF DATA FOR FIRST EXPERIMENT

Our hypothesis is that the better the scene leader, the better is the performance of the team. The following representative results are obtained (see Tables 4-1 to 4-4):

SL Skill	Nozz/ Hosemen Skill	Elec Skill	Mean Time	Standard Error	Median Time	Mean Intact Inflammables	Standard Error	Median Intact Inflammables
0.9	0.5	0.1	78.63	7.20	**58.59**	39.46	2.38	30.38
0.9	0.9	0.9	66.55	3.64	**59.00**	40.58	1.64	41.34
0.5	0.5	0.5	79.69	6.04	**62.50**	35.42	1.44	34.48
0.1	0.9	0.5	79.81	3.64	**74.00**	35.11	1.94	33.77
0.5	0.1	0.9	135.25	10.75	**86.00**	25.75	1.73	20.41
0.1	0.1	0.1	126.80	8.85	**93.71**	23.78	1.51	20.44

Table 4-1. Mean and Median Summaries for 100 Runs for Ignition Rate = 0.5 and Burn-out Rate = 0.25 Ordered by Median Total Time for Firefighting.

SL Skill	Nozz/ Hosemen Skill	Elec Skill	Mean Time	Standard Error	Median Time	Mean Intact Inflammables	Standard Error	Median Intact Inflammables
0.9	0.9	0.9	**66.55**	3.64	59.00	40.58	1.64	41.34
0.9	0.5	0.1	**78.63**	7.20	58.59	39.46	2.38	30.38
0.5	0.5	0.5	**79.69**	6.04	62.50	35.42	1.44	34.48
0.1	0.9	0.5	**79.81**	3.64	74.00	35.11	1.94	33.77
0.1	0.1	0.1	**126.80**	8.85	93.71	23.78	1.51	20.44
0.5	0.1	0.9	**135.25**	10.75	86.00	25.75	1.73	20.41

Table 4-2. Mean and Median Summaries for 100 Runs for Ignition Rate = 0.5 and Burn-out Rate = 0.25 Ordered by Mean Total Time for Firefighting.

SL Skill	Nozz/ Hosemen Skill	Elec Skill	Mean Time	Standard Error	Median Time	Mean Intact Inflammables	Standard Error	Median Intact Inflammables
0.9	0.9	0.9	66.55	3.64	59.00	**40.58**	1.64	41.34
0.9	0.5	0.1	78.63	7.20	58.59	**39.46**	2.38	30.38
0.5	0.5	0.5	79.69	6.04	62.50	**35.42**	1.44	34.48
0.1	0.9	0.5	79.81	3.64	74.00	**35.11**	1.94	33.77
0.5	0.1	0.9	135.25	10.75	86.00	**25.75**	1.73	20.41
0.1	0.1	0.1	126.80	8.85	93.71	**23.78**	1.51	20.44

Table 4-3. Mean and Median Summaries for 100 Runs for Ignition Rate = 0.5 and Burn-out Rate = 0.25 Ordered by Mean Intact Inflammables.

SL Skill	Nozz/ Hosemen Skill	Elec Skill	Mean Time	Standard Error	Median Time	Mean Intact Inflammables	Standard Error	Median Intact Inflammables
0.9	0.9	0.9	66.55	3.64	59.00	40.58	1.64	**41.34**
0.5	0.5	0.5	79.69	6.04	62.50	35.42	1.44	**34.48**
0.1	0.9	0.5	79.81	3.64	74.00	35.11	1.94	**33.77**
0.9	0.5	0.1	78.63	7.20	58.59	39.46	2.38	**30.38**
0.1	0.1	0.1	126.80	8.85	93.71	23.78	1.51	**20.44**
0.5	0.1	0.9	135.25	10.75	86.00	25.75	1.73	**20.41**

Table 4-4. Mean and Median Summaries for 100 Runs for Ignition Rate = 0.5 and Burn-out Rate = 0.25 Ordered by Median Intact Inflammables.

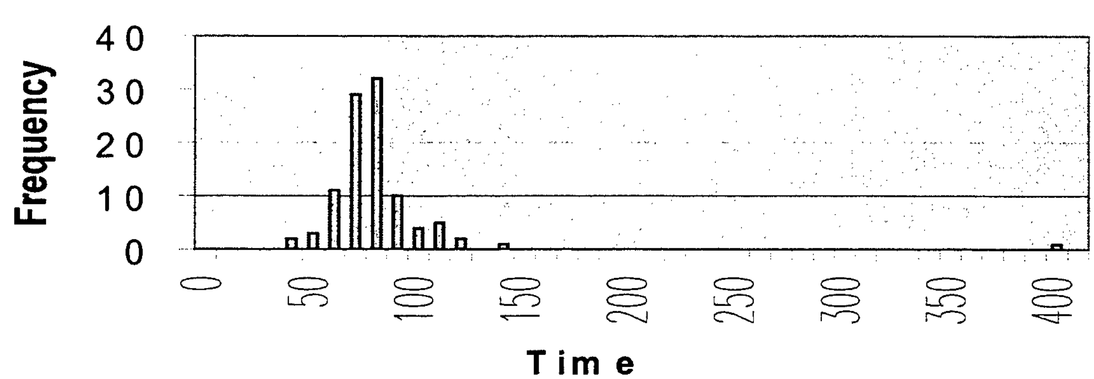

Figure 4-1. Histogram for Total Time for Firefighting for Ignition Rate = 0.5, Burn-out Rate = 0.25 and all Members with Skill Level 0.9.

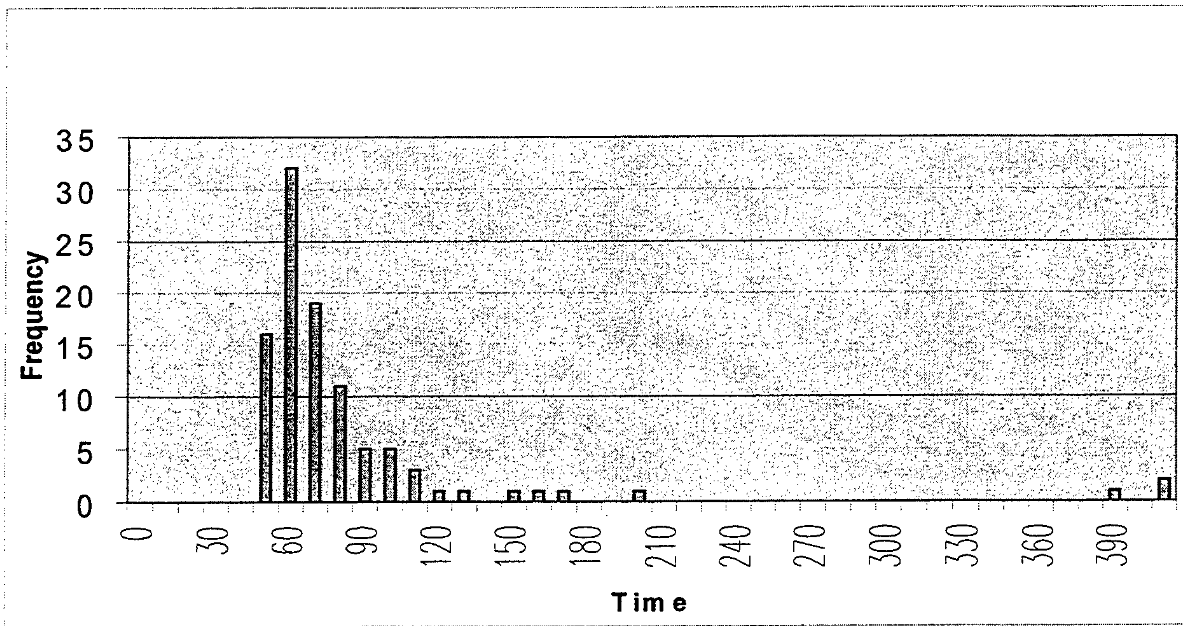

Figure 4-2. Histogram for Total Time for Firefighting for Ignition Rate=0.5, Burn-out Rate=0.25 and all Members with Skill Level 0.5.

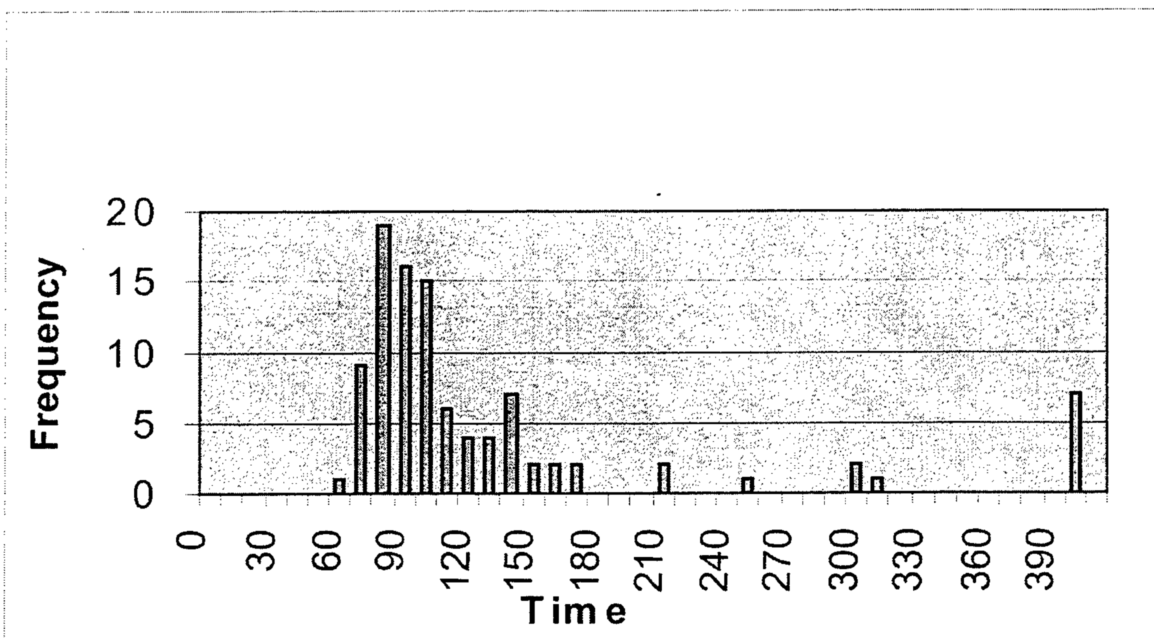

Figure 4-3. Histogram for Total Time for Firefighting for IgnitionRate=0.5, Burn-out Rate=0.25 and all Members with Skill Level 0.1.

The histograms show that the 400-minute cases for total time for firefighting are more likely to occur when the skill level is 0.1. The tables also show the most important influence on total time for firefighting is low skill (0.1) of the hosemen and nozzlemen. The amount of intact inflammables (unburned material) appears to correlate well with average team skill.

C. ANALYSIS OF DATA FOR SECOND EXPERIMENT

We next double the pre-extinguishing ignition rate to 1, and burn-out rate to 0.5 (see Tables 4-5 to 4-8). Results are similar, except mean and median times are smaller because the fire progresses more quickly.

SL Skill	Nozz/ Hosemen Skill	Elec Skill	Mean Time	Standard Error	Median Time	Mean Intact Inflammables	Standard Error	Median Intact Inflammables
0.9	0.9	0.9	**46.63**	1.66	43.00	27.09	1.53	22.46
0.5	0.9	0.9	**47.18**	1.13	45.32	25.80	1.51	21.61
0.9	0.9	0.5	**47.48**	1.23	43.00	25.59	1.53	21.51
0.9	0.5	0.9	**49.09**	1.31	46.55	24.67	1.61	19.83
0.9	0.5	0.1	**49.25**	1.32	46.00	20.77	1.14	17.89
All skills are 0.5,P(flashover)=0.35			**54.31**	3.97	51.50	10.23	1.04	9.5
0.1	0.9	0.5	**56.04**	2.86	48.00	19.79	0.70	18.96
0.5	0.5	0.5	**63.49**	6.73	46.00	26.64	1.88	21.94
0.5	0.1	0.9	**96.05**	7.70	60.50	21.39	1.09	19.28
0.1	0.1	0.1	**100.77**	8.00	68.00	17.68	0.44	17.49

Table 4-5. Mean and Median Summaries for 100 Runs for Ignition Rates = 1, Burn-out Rate = 0.5 Ordered by Mean Total Time for Firefighting.

SL Skill	Nozz/ Hosemen Skill	Elec Skill	Mean Time	Standard Error	Median Time	Mean Intact Inflammables	Standard Error	Median Intact Inflammables
0.9	0.9	0.9	46.63	1.66	**43.00**	27.09	1.53	22.46
0.9	0.9	0.5	47.48	1.23	**43.00**	25.59	1.53	21.51
0.5	0.9	0.9	47.18	1.13	**45.32**	25.80	1.51	21.61
0.5	0.5	0.5	63.49	6.73	**46.00**	26.64	1.88	21.94
0.9	0.5	0.1	49.25	1.32	**46.00**	20.77	1.14	17.89
0.9	0.5	0.9	49.09	1.31	**46.55**	24.67	1.61	19.83
0.1	0.9	0.5	56.04	2.86	**48.00**	19.79	0.70	18.96
All skills are 0.5,P(flashover)=0.35,			54.31	3.97	**51.50**	10.23	1.04	9.5
0.5	0.1	0.9	96.05	7.70	**60.50**	21.39	1.09	19.28
0.1	0.1	0.1	100.77	8.00	**68.00**	17.68	0.44	17.49

Table 4-6. Mean and Median Summaries for 100 Runs for Ignition Rate = 1, Burn-out Rate = 0.5 Ordered by Median Total Time for Firefighting.

SL Skill	Nozz/ Hosemen Skill	Elec Skill	Mean Time	Standard Error	Median Time	Mean Intact Inflammables	Standard Error	Median Intact Inflammables
0.9	0.9	0.9	46.63	1.66	43.00	**27.09**	1.53	22.46
0.5	0.5	0.5	63.49	6.73	46.00	**26.64**	1.88	21.94
0.5	0.9	0.9	47.18	1.13	45.32	**25.80**	1.51	21.61
0.9	0.9	0.5	47.48	1.23	43.00	**25.59**	1.53	21.51
0.9	0.5	0.9	49.09	1.31	46.55	**24.67**	1.61	19.83
0.5	0.1	0.9	96.05	7.70	60.50	**21.39**	1.09	19.28
0.9	0.5	0.1	49.25	1.32	46.00	**20.77**	1.14	17.89
0.1	0.9	0.5	56.04	2.86	48.00	**19.79**	0.70	18.96
0.1	0.1	0.1	100.77	8.00	68.00	**17.68**	0.44	17.49
All skills are 0.5,P(flashover)=0.35,			54.31	3.97	51.50	**10.23**	1.04	9.5

Table 4-7. Mean and Median Summaries 100 Runs for Ignition Rate = 1, Burn-out Rate = 0.5 Ordered by Mean Number of Intact Inflammables.

SL Skill	Nozz/ Hosemen Skill	Elec Skill	Mean Time	Standard Error	Median Time	Mean Intact Inflammables	Standard Error	Median Intact Inflammables
0.9	0.9	0.9	46.63	1.66	43.00	27.09	1.53	**22.46**
0.5	0.5	0.5	63.49	6.73	46.00	26.64	1.88	**21.94**
0.5	0.9	0.9	47.18	1.13	45.32	25.80	1.51	**21.61**
0.9	0.9	0.5	47.48	1.23	43.00	25.59	1.53	**21.51**
0.9	0.5	0.9	49.09	1.31	46.55	24.67	1.61	**19.83**
0.5	0.1	0.9	96.05	7.70	60.50	21.39	1.09	**19.28**
0.1	0.9	0.5	56.04	2.86	48.00	19.79	0.70	**18.96**
0.9	0.5	0.1	49.25	1.32	46.00	20.77	1.14	**17.89**
0.1	0.1	0.1	100.77	8.00	68.00	17.68	0.44	**17.49**
All skills are 0.5,P(flashover)=0.35,			54.31	3.97	51.50	10.23	1.04	**9.5**

Table 4-8. Mean and Median Summaries for 100 Runs for Ignition Rate = 1,Burn-out Rate = 0.5 Ordered by Median Number of Intact Inflammables.

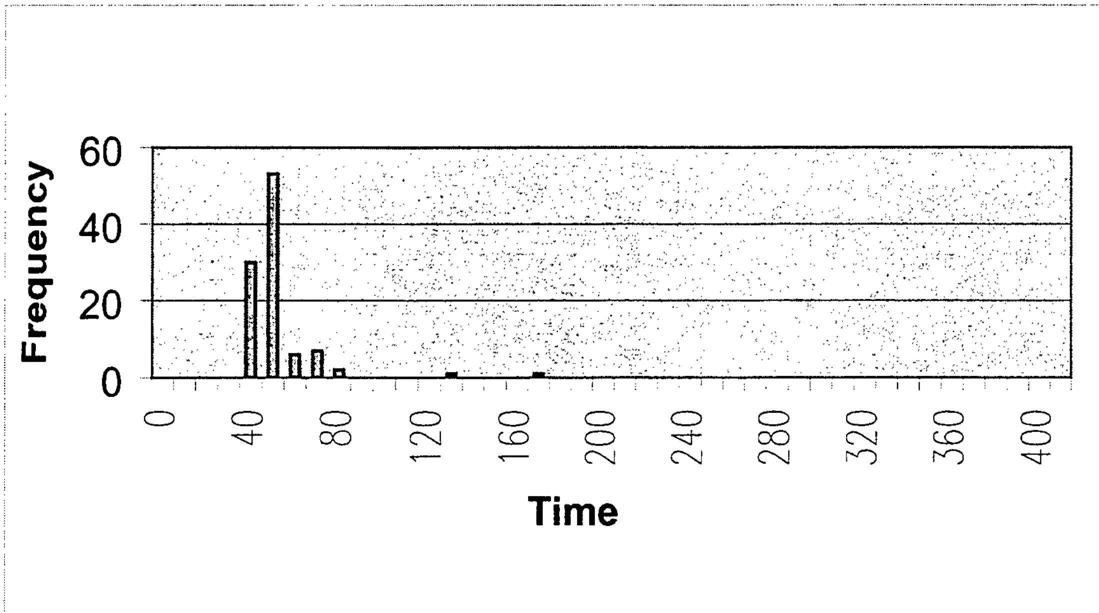

Figure 4-4. Histogram for Total Time for Firefighting for Ignition Rate=1,Burn-out Rate=0.5 and all Members with Skill Level 0.9.

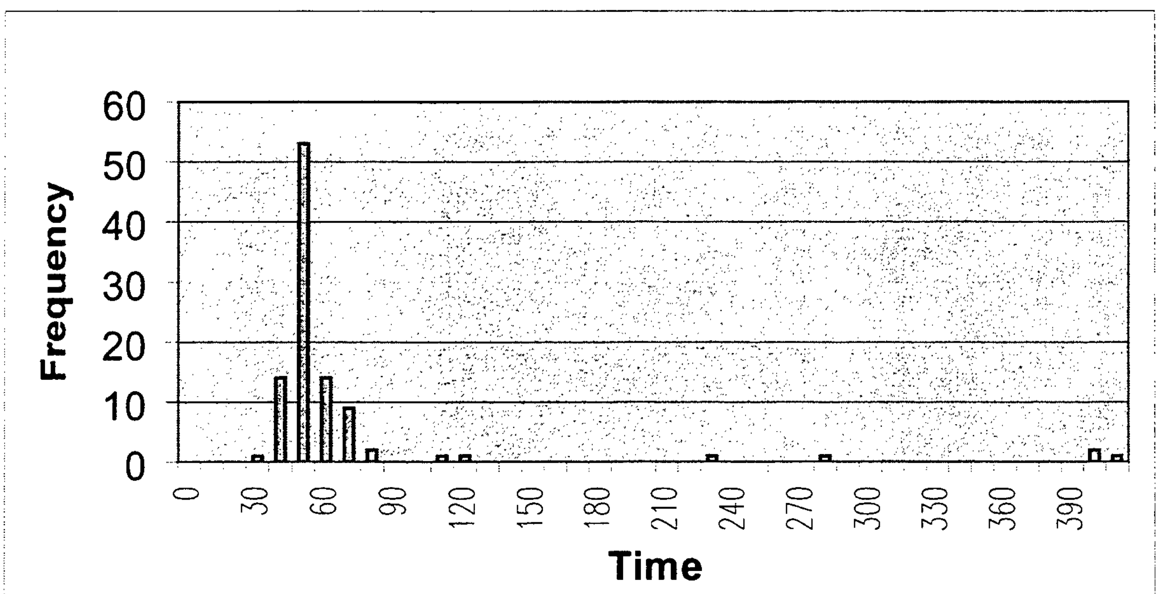

Figure 4-5. Histogram for Total Time for Firefighting for Ignition Rate=1,Burn-out Rate=0.5 and all Members with Skill Level 0.5.

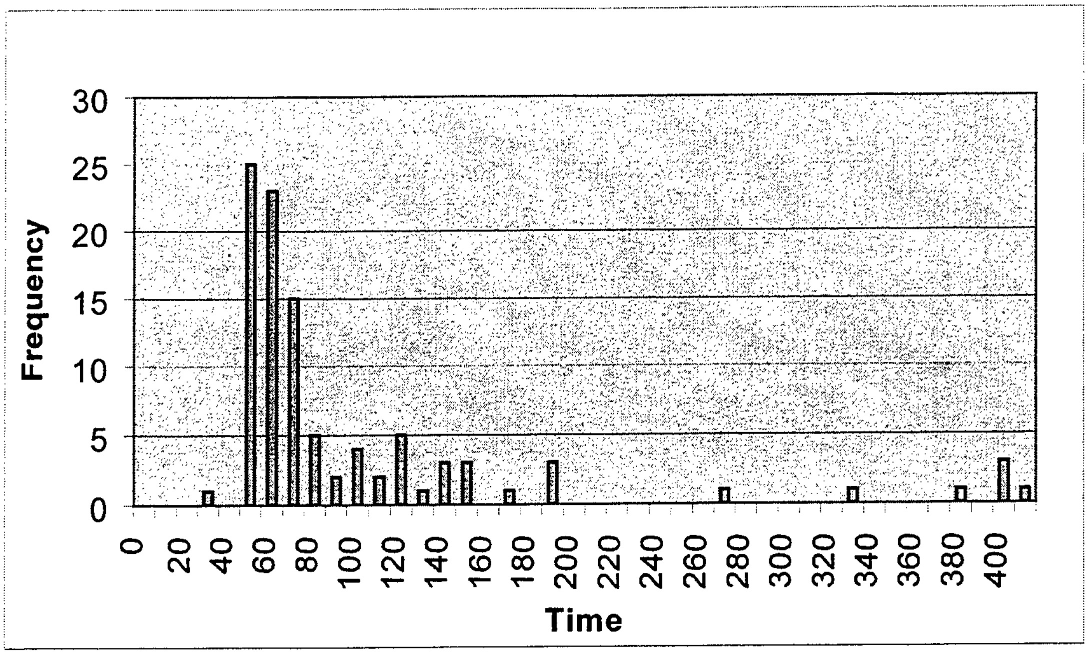

Figure 4-6. Histogram for Total Time for Firefighting for Ignition Rate=1,Burn-out Rate=0.5 and all Members with Skill Level 0.1.

.One hundred trials with a constant 35% probability of flashover (added to the original model, and independent of fire state), all members with skill levels 0.5, were also done. The objective of the experiment is to show that a constant probability of flashover increases the number of flashover cases, and decreases the amount of unburned inflammables. The experiment had 39 flashover cases (note that the simulation tests for flashover when the state of fire changes). When compared to a similar experiment (for same skill levels and rates) where the probability of flashover is not constant (see equation 3.11), the mean intact inflammables decreases significantly.

D. NEAR DETERMINISTIC CASES

In order to analyze the performance of teams when the fire does not have a random component, runs with a near deterministic fire model were carried out for homogeneous teams (all with the same skill level), and probability of flashover given by equation 3.11 (see Tables 4-9 and 4-10). The fire model is near deterministic, because there is intrinsic randomness in some programming rules that can not be changed.

Skill Levels	Mean Time	Standard Error	Median Time	Mean Intact Inflammables	Standard Error	Median Intact Inflammables
all 0.9	54.32	0.36	53.50	58.39	1.65	65.17
all 0.5	67.15	0.19	67.00	48.32	0.81	52.59
all 0.1	105.86	0.52	106.12	36.19	1.06	38.28

Table 4-9. Near Deterministic Cases for Ignition Rate 0.5 and Burn-out Rate 0.25

Skill Levels	Mean Time	Standard Error	Median Time	Mean Intact Inflammables	Standard Error	Median Intact Inflammables
all 0.9	39.39	0.30	39.00	26.12	0.60	25.35
all 0.5	46.54	0.18	46.00	19.49	0.10	20.17
all 0.1	55.85	0.16	56.00	19.89	0.28	19.16

Table 4-10. Near Deterministic Cases for Ignition Rate 1 and Burn-out Rate 0.5.

The results above show that the near deterministic cases have lower mean time than the non-deterministic stochastic cases. The durations of actions for the near deterministic cases have fixed means that depend on the skills, and have no variance. The final amount of unburned material is larger (about the same for case where all skill levels are 0.9 and ignition rate 1 and burn-out rate 0.5) when there is no random fire spread, flashover, and reflash. The effects of randomness on the mean and median times increases more substantially as the skill levels decrease (compare to table 4-8).

E. CONCLUSIONS

The performance of a team of firefighters with the same skills seems to be different for cases with different pre-extinguishing rates in the three different experiments. The total time to complete all actions is the most sensitive to team members skill levels. When the fire spreads faster, and the amount of material that burns out is very high, the percentage of intact inflammables at the end of action is going to be low, no matter what the composition of a team. On the other hand, when fire spreads more slowly, different teams produce different results; the fire seems more difficult to extinguish. Flashover occurs in almost every run with one hundred trials at least once for all cases. The simulation shows that the skills of the electrician do not much affect the overall team performance since an electrician skill level 0.5 and the rest of the team skill level 0.9 (added to the second experiment) do not show a great difference compared to a team with all members having skill level 0.9. Two simulations also added to the second experiment (one for the scene leader skill level 0.5 and the rest of the team 0.9, and other for the hosemen/nozzlemen skill level 0.5 and the rest of the team 0.9) show that when the skill levels for the hosemen/nozzlemen decrease, the performance of the team also decreases. A skilled scene leader is important for the coordination of actions, and for the readiness before extinguishment, but skilled hosemen and nozzlemen, who are responsible for the majority of actions, are even more important.

F. FUTURE WORK

This thesis can be used as a basis for study of extended and enhanced models and control tactics. New team members and new actions and procedures to be carried out in a fire environment can be added. Parameters for ignition rate, burn-out rate and type of fire can be easily changed; new anti-fire technology can affect the performance of the team, such as thermal imagery devices, and alternative, enhanced, mathematical models for the spread of fire and smoke, can be used to simulate behavior of fire, including the spread of fire to other compartments, and the dynamic allocation of firefighters to counter and control that spread.

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APPENDIX A. FIRE AGENT SPECIAL RULES

The fire agent is specified by a mathematical model that handles the normal Gaussian stochastic case of a growing fire. This mathematical model, implemented in Prolog, computes and updates the conditions of fire size, amount of smoke, and number of intact inflammables inside a compartment for all ongoing fires. It also handles the cases when a fire can suddenly flare and ignite all inflammables inside (flashovers) (Figure A-1).

```
/* The fifteen lines below show how the normal case of a  Gaussian fire spread with total
flashover possible (see equations 3.5-3.11) is handled. */
 special_agent3(Loc,S,T,NS) :-
  member(fire(FSize,Loc),S), member(inflammables(C,Loc),S),
  member(smoke(SSize,Loc),S),
/*Next three lines define the parameters for the fire spread*/
  start_state(SS),member(inflammables(CO,Loc),SS),
  C>0.001, Phi is FSize/(100*C), randnum2(UU), U is UU+0.5, steptime(ST),
  ignition_rate(Loc,Irate), burnout_rate(Loc,Brate),
/*Next six lines show the fire spread when there is no flashover*/
/*Fire growth is computed*/
  ((U>Phi, FGrowth is Irate*FSize*(C/CO)*ST, sqrt(FGrowth,Si),
/*Burn out growth is computed*/
  BGrowth is Brate*FSize*ST,
  sqrt(BGrowth,Sm), normalrandnum2(Ui), normalrandnum2(Um),
/*Random components are computed*/
  RGrowth is Ui*Si, RBurnout is Um*Sm,
/*New size of fire and percentage of inflammables are computed*/
  NSize is FSize+FGrowth-BGrowth+RGrowth-RBurnout,
  NC is C-FGrowth-  RGrowth,
/*The size of smoke is also  computed here.*/
  NSSize is SSize+((2.4-SSize)*0.1),
/*Diode expressions do not let the size of fire and the number of inflammables go below
zero or above 100.*/
  diode1(NSize,XNSize), diode(XNSize,XXNSize),
  diode1(NC,XNC),diode(XNC,XXNC) );
/*A flashover may happen and ignite all inflammables inside*/
   (U=<Phi, XXNSize is FSize+C, XNC=0, NSSize is SSize + ((2.4-Ssize)*0.1)) ),
/*The changed state of fire is calculated */
  delete(fire(FSize,Loc),S,S2),
  delete(inflammables(C,Loc),S2,S3),
  delete(smoke(SSize,Loc),S3,S4), fire_deletions(Loc,S4,S5),
/*Next fact deals with concurrent alarms*/
 (((FSize>1.5; concurrent_alarm_raising_act(T,Loc)),
  \+ member(alarmed(fire,Loc),S), S6=[alarmed(fire,Loc)|S5] ); S6=S5),
  NS=[fire(XXNSize,Loc), smoke(NSSize,Loc),
   inflammables(XXNC,Loc)|S6],
   ((\+ member(alarmed(fire,Loc),NS); member(alarmed(fire,Loc),S));
   alarm_aborts(Loc,NT,NS) ), !.
```

Figure A-1.   Normal Case of a Growing Fire with Possible Total Flashover.

```
/*A fire can randomly reflash on rare occasions; if an action is being done
there, the reflash will be noticed immediately, else wait for alarm. This
rule also handles side effects of reflash of a fire.*/
special_agent3(Loc,S,T,NS) :- \+ member(fire(_,Loc),S), randnum(R),
  mod(R,113,RR), RR = 1, randnum(R2), mod(R2,100,RR2),
  FSize is 0.005*(1+RR2),
  fire_deletions(Loc,S,XS1), delete(firetype(Loc,_),XS1,S1),
  randnum(R3), mod(R3,100,RR3),
  ((RR3>80, PT=firetype(Loc,'c')); PT=firetype(Loc,'a')),
  ((concurrrent_alarm_raising_act(T,Loc),
   NS=[fire(FSize,Loc), smoke(0,Loc), alarmed(fire,Loc), PT|S1],
   alarm_aborts(Loc,NT,NS) );
   NS=[fire(FSize,Loc), smoke(0,Loc),PT|S1] ),
   write('%%%% Fire flared up in '), write(Loc), write('.'), nl, !.
```

Figure A-2. Reflash Case.

The fire can randomly reflash on rare occasions; if an action is being done in the same compartment, this will be noticed immediately, else the fire must grow enough to trigger the alarm (Figure A-2). Extinguishment is implemented similarly except the ignition and burn-out rates are computed as in equations 3.12 and 3.13 (Figure A-3).

```
/* The lines below show how the case where the fire is being extinguished is handled.
Note that both ignition and burn-out rates are recalculated. The duration of the action is
also computed in real time.

special_agent3(Loc,S,T,NS) :- \+ member(wrong_tool(Loc),S),
 member(fire(FSize,Loc),S), member(inflammables(C,Loc),S),
 member(smoke(SSize,Loc),S), start_state(SS),
 member(inflammables(CO,Loc),SS),
 C>0.001, act (A,extinguish(Loc,Tool),TS,TE), TS =< T, T < TE,
 steptime(ST),
/*Ignition and burn-out rates are recalculated */
 ignition_rate(Loc,IR),burnout_rate(Loc,BR),skill(_,SL),F1 is (-10)*SL,
 exp(F1,F2),Extinguishrate is IR*F2,exp(SL,F3),Newburnoutrate is BR*F3,
 FGrowth is Extinguishrate*FSize*(C/CO)*ST,
 sqrt(FGrowth,Si),BGrowth is Newburnoutrate*FSize*ST,
 sqrt(BGrowth,Sm), normalrandnum2(Ui), normalrandnum2(Um),
 RGrowth is Ui*Si, RBurnout is Um*Sm,
 NSize is FSize+FGrowth-BGrowth+RGrowth-RBurnout,
 NC is C-FGrowth- RGrowth,
 NSSize is SSize+((2.4-SSize)*0.1),
 diode1(NSize,XNSize), diode(XNSize,XXNSize),
 diode1(NC,XNC),diode(XNC,XXNC),
 delete(fire(FSize,Loc),S,S2), delete(inflammables(C,Loc),S2,S3),
 delete(smoke(SSize,Loc),S3,S4), fire_deletions(Loc,S4,S5), NT is T+1,
 NS=[fire(XXNSize,Loc),
 smoke(NSSize,Loc),inflammables(XXNC,Loc)|S5],
 ((TE < NT, retract(act(A,extinguish(Loc,Tool),TS,TE)),
 write('%% Extinguish act is being extended by one minute.'), nl,
  NTE is TE+1, assertz(act(A,extinguish(Loc,Tool),TS,NTE)),
  retract(state(TE,SE)), asserta(state(NTE,SE)), update_status_times(NTE) );
  true), !.
```

Figure A-3. Extinguishing Action Rule.

APPENDIX B. SPREADSHEET FIRE MODELING

A spreadsheet simulation of the stochastic fire model was used to help visualize how the fire spread model works before the implementation of the Prolog simulation. The simulation was written in Visual Basic with an Excel interface by Professor Jacobs. One part modeled the normal spread of fire, and one part modeled the behavior of fire during extinguishment.

The worksheet "Parameters" includes the parameters used. The fire spread is governed by the parameters lambda (λ) and mu (μ), determined by the inflammable material inside a compartment. Lambda is the rate that combustibles catch fire (ignition rate) while mu is the rate that inflammables on fire are burned out (burn-out rate) before firefighting action (see Figure 1). The model equations are (3.5) and (3.10). The skill level of the team member in charge of the extinguishment is a parameter that ranges between 0 and 1. It is used to calculate the new values of lambda and mu after the beginning of the firefighting action (see Figure B-1). The values of mu and lambda appear in equations (3.12) and (3.13) for different skill levels. The fire can be subject to flashovers as a function of the fire size and the amount of inflammables intact. Other parameters are the time step for the simulation and a mean time for team to arrive; the latter is exponentially distributed unlike the Prolog simulation. Other actions, such as "equip", "go to compartment" and "deenergize", are not modeled in the spreadsheet simulation.

	nothing done	firefighters action
Ignition rate λ	1	0.2
Burn-out rate μ	0.1	1

Amount of material not on fire: C(0) = 100

Amount of material on fire at time 0: X(0) = 1

Step size h : 0.05 minutes

Mean time until team arrives (exponential time): 3 minutes

Probability of flashover (at time t) =
c*(1-exp(-gamma*h* (X(t)/C(0))*(C(t)/C(0))))

Flashover constant gamma : 1

Flashover binary variable c: 0 (no flashover) or 1 (flashover)

Figure B-1. "Parameters"Worksheet.

The size of fire X(t) and the number of intact inflammables C(t) are updated according to Gaussian fire spread model in equations 3.5, 3.8, 3.9, and 3.10.

Figure B-2 shows an example run. The case displayed shows that a fire quickly spread over the compartment. Within six minutes all inflammables were on fire, and after eighteen minutes more, all inflammables burned out despite the intervention of a team of firefighters.

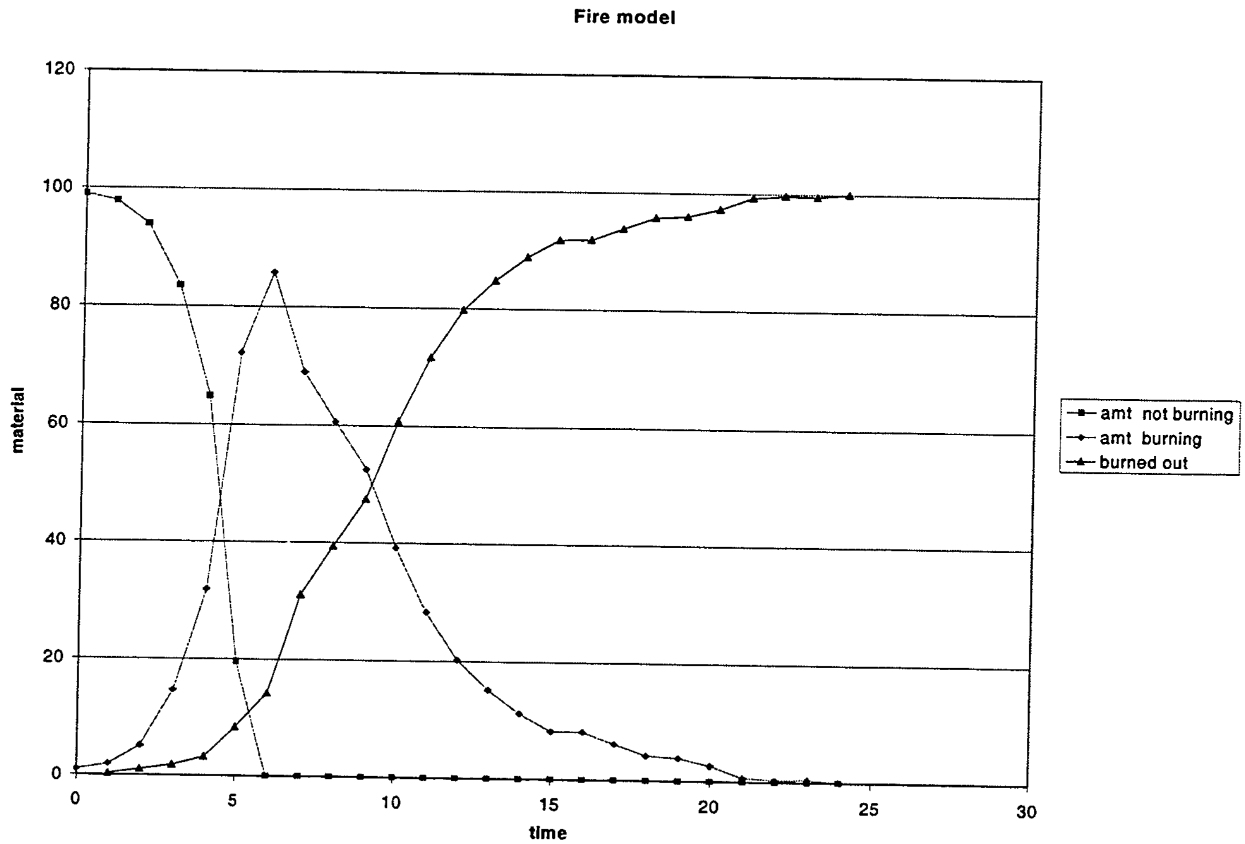

Figure B-2. Example of the State of Material in a Compartment On Fire.

Such data comes from a worksheet "Results" that also shows the time that the team of firefighters arrive, the time the fire is out, the amount of material burned, the amount of material not burned, and the size of fire when the team arrives (see Figure B-3).

time	amount on fire	amount not on fire	amount burned and out
0	1	99	
1	0.662834	99	0.337166
2	2.068585	98.01253	0
3	3.658883	95.90479	0.436323
4	7.626982	91.35711	1.015904
5	9.973527	87.31762	2.708848
6	11.51789	83.79152	4.690586
7	15.77426	77.26222	6.963521
8	15.81027	72.44835	11.74139
9	22.45131	62.81107	14.73762
10	32.6607	47.62938	19.70992
11	42.34867	34.34967	23.30167
12	46.29677	22.541	31.16223
13	39.47127	18.57668	41.95205
14	40.02299	13.36887	46.60813
15	35.33816	9.909097	54.75274
16	31.77973	7.313057	60.90721
17	29.81238	4.163426	66.02419
18	23.80992	3.254122	72.93596
19	15.14419	3.453611	81.40219
20	10.09625	3.256789	86.64696
21	6.391095	3.520767	90.08814
22	5.815516	3.384065	90.80042
23	4.307266	2.985767	92.70697
24	4.24357	2.51188	93.24455
25	1.904942	2.859917	95.23514
26	1.956499	2.555544	95.48796
27	1.534735	2.408332	96.05693
28	1.068158	2.538853	96.39299
29	0.878231	2.365991	96.75578
30	0.186769	2.53091	97.28232
31	0.107863	2.57163	97.32051
32	0.251496	2.549366	97.19914
33	0.351985	2.555454	97.09256
34	0.592594	2.430671	96.97673
35	0.661035	2.518897	96.82007
36	0.86549	2.599733	96.53478
37	0	2.766028	97.23397

time team arrives	**time fire out**
0.56071	37
amount not burned	**amt burned**
2.766028	97.23397

size of fire when team arrives

0.662834

Figure B-3. Example " Results" Output.

APPENDIX C. AGENTS' TASKS

This part is the work of Professor Neil Rowe and students. It describes the possible actions for team members.

Equip

Preconditions: team must be at repair locker

Agent in charge of the action: scene leader

Go from repair locker to location of fire

Preconditions: team must be equipped at repair locker

Agent in charge of the action: scene leader

Order to report the size of fire

Preconditions: team must be at location of fire

Agent in charge of the action: Command Center

Report the size of fire

Preconditions: agent must be ordered to report the size of fire

Agent in charge of the action: scene leader

Record the size of fire

Preconditions: scene leader must report the size of fire

Agent in charge of the action: Command Center

Order deenergize

Preconditions: team must be at location of fire

Agent in charge of the action: scene leader

Deenergize

Preconditions: team must be at location of fire

Agent in charge of the action: electrician

Report deenergized

Preconditions: agent must be ordered to deenergize

Agent in charge of the action: scene leader

Set boundaries of fire

Preconditions: team must be at location of fire, fire must have been recorded

Agent in charge of the action: scene leader

Order tend hose

Preconditions: team must be at location of fire, equipped, deenergized reported, boundaries set

Agent in charge of the action: nozzleman or hoseman

Report hose tended

Preconditions: agent must have been ordered to tend hose

Agent in charge of the action: hoseman or nozzleman

Approach fire

Preconditions: team must be at location of fire, equipped, deenergized reported, boundaries set, and fire has not already been approached

Agent in charge of the action: nozzleman or hoseman

Extinguish

Preconditions: team must be at location of fire, equipped, deenergized reported, boundaries set, fire approached, reported tended hose

Agent in charge of the action: nozzleman or hoseman

Order verify fire out

Preconditions: team must be at location of fire and equipped

Agent in charge of the action: scene leader

Verify fire out

Preconditions: team must be at location of fire, agent must have been ordered to verify if the fire is out

Agent in charge of the action: nozzleman

Report fire out verified

Preconditions: agent must have been ordered to verify if fire is out

Agent in charge of the action: nozzleman

Estimate water

Preconditions: team must be at location of fire and fire is out

Agent in charge of the action: scene leader

Order desmoke

Preconditions: fire is out

Agent in charge of the action: scene leader

Desmoke

Preconditions: team must be at location of fire, fire is out, and there is smoke in the compartment

Agent in charge of the action: electrician

Report desmoked

Preconditions: agent must have been ordered to desmoke

Agent in charge of the action: electrician

Order dewater

Preconditions: water has been estimated

Agent in charge of the action: scene leader

Dewater

Preconditions: team must be at location of fire, fire is out, and there is water in the compartment, and water has been estimated

Agent in charge of the action: nozzleman or hoseman

Report dewatered

Preconditions: agent must have been ordered to dewater

Agent in charge of the action: nozzleman or hoseman

Order test for safe oxygen/ gases

Preconditions: fire is out

Agent in charge of the action: scene leader

Test oxygen tester

Preconditions: team equipped

Agent in charge of the action: nozzleman or hoseman

Test oxygen/gases

Preconditions: team equipped and at location of fire, fire is out, oxygen tester is OK, oxygen/gases level is not safe

Agent in charge of the action: nozzleman or hoseman

Report oxygen/gases safe

Preconditions: agent must have been ordered to test for safe oxygen/gases

Agent in charge of the action: nozzleman or hoseman

Ventilate

Preconditions: team equipped and at location of fire, fire is out

Agent in charge of the action: nozzleman or hoseman

Order watch for reflash

Preconditions: fire is out

Agent in charge of the action: scene leader

Watch for reflash

Preconditions: fire is out, oxygen/gases are safe, and there is no watch for reflash

Agent in charge of the action: nozzleman or hoseman

Report watched for reflash

Preconditions: agent must have been ordered to watch for reflash

Agent in charge of the action: nozzleman or hoseman

Go from location of fire to repair locker

Precondition: if watch for reflash reported: desmoked reported, dewatered reported, safe oxygen/gases reported, team is not at repair locker; if watch for reflash not reported: desmoked reported, dewatered reported, safe oxygen/gases reported, team is not at repair locker and ordered watch for reflash

Agent in charge of the action: scene leader

Store equipment

Precondition: team must be equipped at repair locker

Agent in charge of the action: scene leader

Debrief team

Precondition: team must not be equipped at repair locker, fire is out, watch for reflash reported, desmoked reported, dewatered reported, safe oxygen/gases reported

Agent in charge of the action: scene leader

The simulation used probabilities for random changes. When approaching or extinguishing the fire, there is a probability of 15% that a casualty is present; when desmoking, dewatering, or extinguishing the fire, there is a probability of 8% that a team member accidentally turns the power on; and when desmoking, dewatering or storing, there is a probability of 8% that a casualty is present; when testing gases or oxygen, there is a probability of 30% that gases or oxygen are not safe. These are illustrative values that can be changed at the will of an analyst.

Here is an example of a possible sequence of actions.

As soon as the alarm goes off, the Command Center orders the scene leader to put out the fire. The scene leader orders all team members to their repair locker to get equipped. Then the scene leader takes the team to the compartment on fire and reports the size of fire to the Command Center. The scene leader tells the electrician to deenergize the area. Once the area is reported deenergized and the size of fire is recorded, the scene leader has to set the boundaries of the fire. Now it is safe for the nozzleman to order the hoseman to tend the hose. After the report of tended hose, the nozzleman and the hoseman are ready to approach fire, and then begin extinguishment using the appropriate tool. If the tool fails to extinguish the fire within a certain time (with a given probability of failure), they can change tools, and continue the action. After verifying the fire is out, the nozzleman reports it to the scene leader. The scene leader then estimates the amount of water in the compartment, gives orders to desmoke the area, gives orders to test for safe gases and oxygen, and gives orders to dewater. Either the nozzleman or the hoseman can carry out the testing of oxygen and gases and the removal of water; the electrician removes smoke. If it is still unsafe for gases or oxygen, the scene leader orders the electrician to ventilate the area. When these actions are completed, they are reported to the scene leader. The scene leader has to order a watch for a possible reflash before leaving the area. The scene leader takes the team from the compartment back to the repair locker where they store the equipment. When the reflash watch terminates, the scene leader debriefs the team and reports that the team was debriefed to the Command Center. The Command Center records that the team was debriefed, and the procedure is finished.

The fire agent behavior is displayed in the following flowchart (fig. C-1).

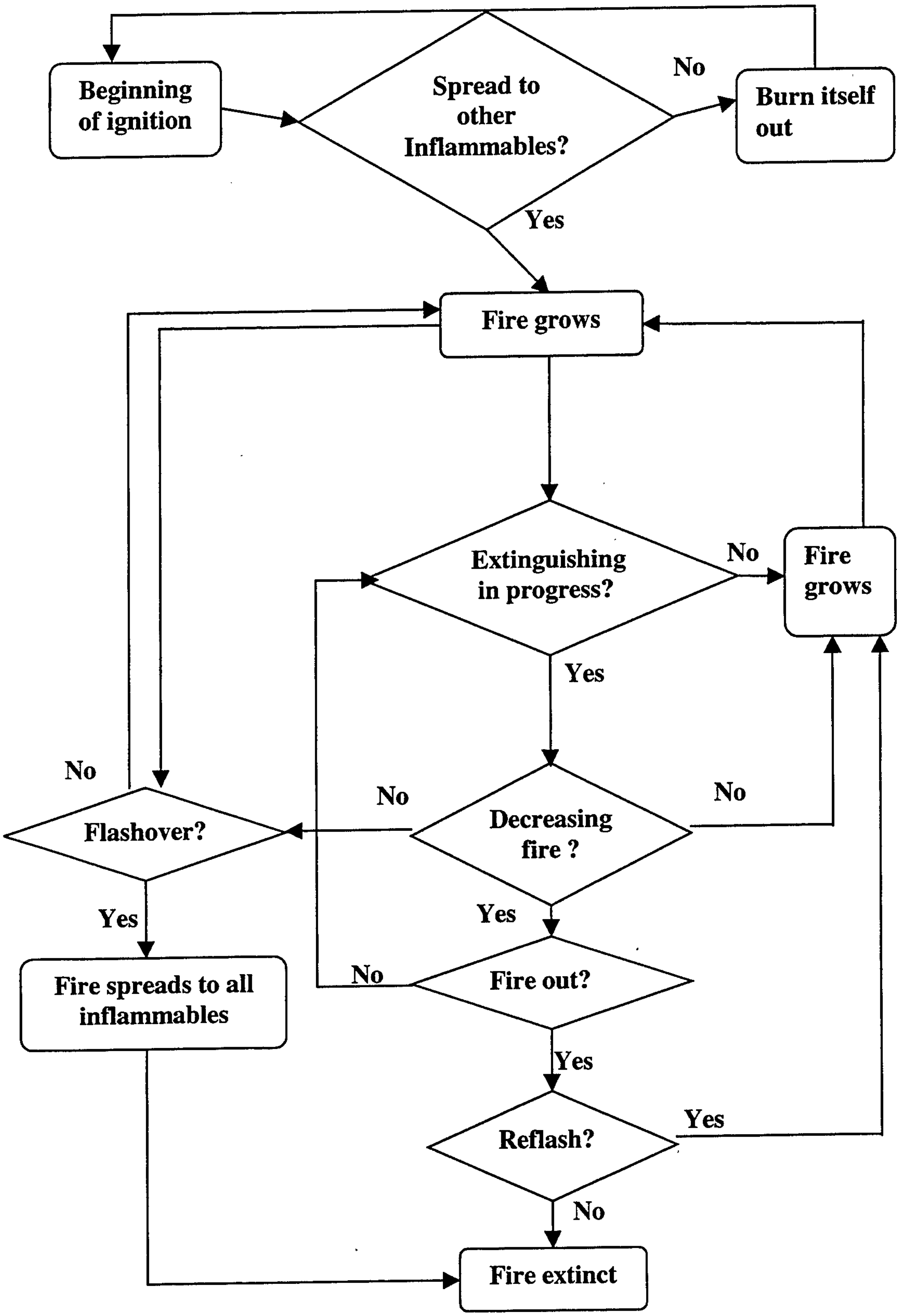

Figure C-1 - Fire Agent Behavior.

APPENDIX D. EXAMPLE ACTOUT FILE

Here is an example of an "actout" file showing the tasks carried out by each agent in a full simulation run. The parameters used for this run are: ignition rate 0.5, burn-out rate 0.25, all team members with skill level 0.9.

Agent fire did
"burn([fire(1,352b),smoke(0,352b),inflammables(99,352b)],[fire(0.944749,352b), inflammables(98.6915,352b),smoke(0.24,352b)])" from 0.0 to 1.0 minutes
The action "burn" done by the fire agent between time 0.0 and 1.0 minutes shows a decrease in the fire size inside compartment 352b (from 1 to 0.944749), an increase in the size of smoke inside the compartment (from 0 to 0.24), and a decrease in the percentage of intact inflammables inside the compartment (from 99 to 98.6915 percent).

Agent fire did
"burn([fire(0.944749,352b),inflammables(98.6915,352b),smoke(0.24,352b)],[fire(1.0158 6,352b), inflammables(97.7957,352b),smoke(0.456,352b)])" from 1.0 to 2.0 minutes

Agent fire did
"burn([fire(1.01586,352b),inflammables(97.7957,352b),smoke(0.456,352b)],[fire(1.5599 8,352b), inflammables(97.2838,352b),smoke(0.6504,352b)])" from 2.0 to 3.0 minutes

Agent fire did
"burn([fire(1.55998,352b),inflammables(97.2838,352b),smoke(0.6504,352b)],[alarmed(fi re,352b), fire(2.02247,352b),inflammables(95.9187,352b),smoke(0.82536,352b)])" from 3.0 to 4.0 minutes

Agent command center did "order (debriefed(team,352b),command center, scene leader)" from 4.0 to 4.28 minutes

Agent fire did
"burn([fire(2.02247,352b),inflammables(95.9187,352b),smoke(0.82536,352b)],[fire(3.41 6,352b), inflammables(94.3547,352b),smoke(0.982824,352b)])" from 4.0 to 5.0 minutes

Agent scene leader did "equip" from 4.28 to 6.85 minutes.

This means the scene leader helps the team get equipped between minutes 4.28 and 6.85.

Agent fire did
"burn([fire(3.41641,352b),inflammables(94.3547,352b),smoke(0.982824,352b)],[fire(5.9 2,352b), inflammables(89.965,352b),smoke(1.12454,352b)])" from 5.0 to 6.0 minutes

Agent fire did
"burn([fire(5.9261,352b),inflammables(89.965,352b),smoke(1.12454,352b)],[fire(7.7521 1,352b), inflammables(84.7063,352b),smoke(1.25209,352b)])" from 6.0 to 7.0 minutes

Agent scene leader did "go(repairlocker,352b)" from 6.85 to 7.97 minutes.
It means that between minutes 6.85 and 7.97 the scene leader took the team from the repair locker to compartment 352b.

Agent fire did
"burn([fire(7.75211,352b),inflammables(84.7063,352b),smoke(1.25209,352b)],[fire(7.66, 352b), inflammables(80.5647,352b),smoke(1.36688,352b)])" from 7.0 to 8.0 minutes

Agent command center did "order (fire(_454788,352b),command center, scene leader)" from 7.97 to 8.24 minutes.

Here the Command Center orders the scene leader to put the fire out in compartment 352b.

Agent scene leader did "order(deenergized(352b),scene leader, electrician)" from 7.97 to 8.23 minutes.

Here the electrician receives an order from the scene leader to deenergize the area of compartment 352b.

Agent fire did "burn([fire(7.66114,352b),inflammables(80.5647,352b),smoke(1.36688,352b)],[fire(6.556,352b), inflammables(77.0206,352b),smoke(1.47019,352b)])" from 8.0 to 9.0 minutes

Agent electrician did "deenergize(352b)" from 8.23 to 9.41 minutes

Agent scene leader did "order (verified(fire_out,352b),scene leader, nozzleman)" from 8.23 to 8.45 minutes.

Agent scene leader did "report (fire(7.66114,352b),command center, scene leader)" from 8.45 to 8.67 minutes.

The scene leader reports the size of fire in compartment 352b to the Command Center.

Agent command center did "record fire(7.66114,352b))" from 9.0 to 10.02 minutes

Agent fire did "burn([fire(6.55156,352b),inflammables(77.0206,352b),smoke(1.47019,352b)],[fire(8.276,352b), inflammables(72.1762,352b),smoke(1.56317,352b)])" from 9.0 to 10.0 minutes

Agent electrician did "report (deenergized(352b),scene leader, electrician)" from 9.41 to 9.69 minutes

Agent fire did "burn([fire(8.27526,352b),inflammables(72.1762,352b),smoke(1.56317,352b)],[fire(11.357,352b), inflammables(65.8635,352b),smoke(1.64685,352b)])" from 10.0 to 11.0 minutes

Agent scene leader did "set (boundaries, 352b)" from 10.02 to 10.9 minutes

Agent nozzleman did "approach (fire, 352b)" from 11.0 to 11.81 minutes

Agent fire did "burn([fire(11.3457,352b),inflammables(65.8635,352b),smoke(1.64685,352b)],[fire(13.114,352b), inflammables(58.9284,352b),smoke(1.72217,352b)])" from 11.0 to 12.0 minutes

Agent nozzleman did "order (tended(hose,352b),nozzleman, hoseman)" from 11.81 to 12.07 minutes.

The nozzleman orders the hoseman to tend the hose.

Agent fire did "burn([fire(13.1148,352b),inflammables(58.9284,352b),smoke(1.72217,352b)],[fire(16.084,352b), inflammables(50.7363,352b),smoke(1.78995,352b)])" from 12.0 to 13.0 minutes

Agent hoseman did "tend(hose,352b)" from 12.07 to 13.14 minutes

Agent fire did "burn([fire(16.0846,352b),inflammables(50.7363,352b),smoke(1.78995,352b)],[fire(13.0

37,352b), inflammables(42.4855,352b),smoke(1.85096,352b)])" from 13.0 to 14.0 minutes

Agent hoseman did "report(tended(hose,352b),nozzleman, hoseman)" from 13.14 to 13.36 minutes.

The hoseman reports that the hose is tended in compartment 352b.

Agent fire did
"burn([fire(13.0379,352b),inflammables(42.4855,352b),smoke(1.85096,352b)],[fire(13.228,352b), inflammables(35.6229,352b),smoke(1.90586,352b)])" from 14.0 to 15.0 minutes

Agent fire did
"burn([fire(13.2281,352b),inflammables(35.6229,352b),smoke(1.90586,352b)],[fire(10.409,352b), inflammables(32.1959,352b),smoke(1.95528,352b)])" from 15.0 to 16.0 minutes

Agent fire did
"burn([fire(10.4092,352b),inflammables(32.1959,352b),smoke(1.95528,352b)],[fire(9.5596,352b), inflammables(29.1744,352b),smoke(1.99975,352b)])" from 16.0 to 17.0 minutes

Agent fire did
"burn([fire(9.55963,352b),inflammables(29.1744,352b),smoke(1.99975,352b)],[fire(8.4067,352b), inflammables(25.4959,352b),smoke(2.03977,352b)])" from 17.0 to 18.0 minutes

Agent fire did
"burn([fire(8.40675,352b),inflammables(25.4959,352b),smoke(2.03977,352b)],[fire(7.8989,352b), inflammables(22.7267,352b),smoke(2.0758,352b)])" from 18.0 to 19.0 minutes

Agent fire did
"burn([fire(7.89891,352b),inflammables(22.7267,352b),smoke(2.0758,352b)],[fire(6.8429,352b), inflammables(19.7633,352b),smoke(2.10822,352b)])" from 19.0 to 20.0 minutes

Agent nozzleman did "extinguish (352b,stream)" from 14.0 to 20.0 minutes.

The nozzleman uses stream to carry out the extinguishment in compartment 352b.

Agent fire did
"burn([wrong_tool(352b),fire(6.84294,352b),inflammables(19.7633,352b),smoke(2.10822,352b)],
[failed(352b,stream),fire(5.38766,352b),inflammables(17.8817,352b),smoke(2.13739,352b)])" from 20.0 to 21.0 minutes

Agent fire did
"burn([fire(5.38766,352b),inflammables(17.8817,352b),smoke(2.13739,352b)],[fire(1.0587,352b), inflammables(17.8602,352b),smoke(2.16365,352b)])" from 21.0 to 22.0 minutes

Agent fire did
"burn([fire(1.05878,352b),inflammables(17.8602,352b),smoke(2.16365,352b)],[fire(0,352b), inflammables(17.866,352b),smoke(2.18729,352b)])" from 22.0 to 23.0 minutes

Agent nozzleman did "extinguish(352b,foam)" from 21.0 to 23.0 minutes.

The nozzleman uses foam to carry out the extinguishment in compartment 352b.

Agent fire did
"burn([alarmed(fire,352b),confronted(fire,352b),fire(0,352b),indicated(boundaries,352b),

tended(hose,352b),reported(tended(hose,352b),nozzleman,hoseman)],[formerfire(0,352b) , water(0,352b)])" from 23.0 to 24.0 minutes

Agent nozzleman did "verify (fire_out,352b)" from 24.0 to 24.88 minutes.

Agent scene leader did "order (safe(oxygen,352b),scene leader,hoseman)" from 24.0 to 24.29 minutes.

The scene leader orders the hoseman to test for safe oxygen.

Agent scene leader did "estimate(water,352b)" from 24.29 to 25.14 minutes

Agent hoseman did "test(oxygen_tester)" from 24.88 to 25.66 minutes

Agent nozzleman did "report(verified(fire_out,352b),scene leader , nozzleman)" from 24.88 to 25.15 minutes.

The nozzleman reports to the scene leader that the fire is out.

Agent scene leader did "order(not(water(_454790,352b)),scene leader, nozzleman)" from 25.14 to 25.42 minutes.

The scene leader orders the nozzleman to remove water from compartment 352b.

Agent nozzleman did "dewater(352b)" from 25.42 to 25.45 minutes.

Water is removed by the nozzleman in compartment 352b.

Agent scene leader did "order(safe(gases,352b),scene leader, nozzleman)" from 25.42 to 25.66 minutes.

The scene leader orders the nozzleman to test for safe gases.

Agent nozzleman did "report(not(water(_454790,352b)),scene leader, nozzleman)" from 25.45 to 25.68 minutes.

The nozzleman reports that water was removed from compartment 352b.

Agent scene leader did "order(watched(reflash,352b),scene leader,hoseman)" from 25.66 to 25.88 minutes.

The scene leader orders the hoseman to set a watch for reflash.

Agent hoseman did "test(oxygen,352b)" from 25.66 to 26.45 minutes

Agent nozzleman did "test(gases,352b)" from 25.68 to 26.56 minutes

Agent scene leader did "order(not(smoke(_454790,352b)),scene leader, electrician)" from 25.88 to 26.09 minutes.

The scene leader orders the electrician to remove the smoke from compartment 352b.

Agent electrician did "desmoke(352b)" from 26.09 to 30.57 minutes

Agent hoseman did "report(safe(oxygen,352b),scene leader,hoseman)" from 26.45 to 26.69 minutes.

The hoseman reports that the oxygen test in compartment 352b is safe.

Agent nozzleman did "report(safe(gases,352b),scene leader,nozzleman)" from 26.56 to 26.81 minutes.

The nozzleman reports that the gases test in compartment 352b is safe.

Agent hoseman did "watch(reflash,352b)" from 26.69 to 42.94 minutes.

The hoseman stays in compartment 352b to watch for a reflash.

Agent electrician did "report(not(smoke(_454790,352b)),scene leader,electrician)" from 30.57 to 30.83 minute.

The electrician reports to the scene leader that the smoke was removed.

Agent scene leader did "go(352b,repairlocker)" from 31.0 to 31.79 minutes.

The scene leader takes the team from compartment 352b back to the repair locker.

Agent scene leader did "store(equipment)" from 31.79 to 32.64 minutes.

The scene leader and the members of the team store the equipment.

Agent hoseman did "report(watched(reflash,352b),scene leader,hoseman)" from 42.94 to 43.16 minutes.

The hoseman reports the end of the watch for reflash to the scene leader.

Agent scene leader did "debrief(team,352b)" from 43.16 to 44.09 minutes.

The scene leader debriefs the team about the fire in compartment 352b.

Agent scene leader did "report(debriefed(team,352b),command center,scene leader)" from 44.09 to 44.36 minutes.

The scene leader reports to the Command Center that the team was debriefed about the fire in compartment 352b.

Agent command center did "record(debriefed(team,352b))" from 45.0 to 46.01 minutes.

The Command Center records that team was debriefed about fire in compartment 352b.

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